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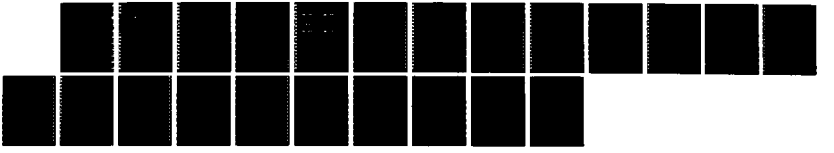

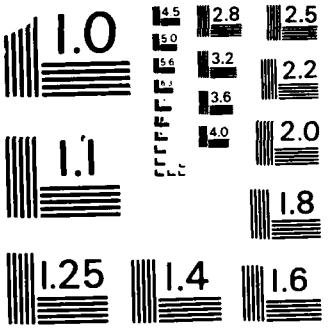

REPORT ON AN INTERLABORATORY ELECTROMIGRATION EXPERIMENT

by
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National Bureau of Standards
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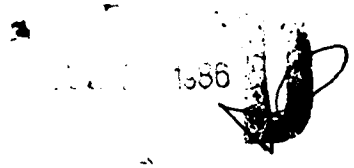

Electromigration is a metallization failure mechanism that is of concern for VLSI reliability. Ambiguities exist in the electromigration characterization of metallizations. These ambiguities are, in general, due to the different test structures and measurement methods used and to the incomplete reporting of the results from such characterizations.

An interlaboratory experiment has been organized to address this problem. The purpose of the experiment is to assess the reproducibility of electromigration characterizations and to establish the technical base needed to develop guidelines for the design of electromigration test structures, for methods to measure the median-time-to-failure (t_{50}) of metallizations, and for reporting characterization measurements. Fourteen laboratories have volunteered to participate in the experiment.

A test chip, NBS-42, was designed for this experiment and is shown in Fig.1. Each quadrant of the chip has five test-line structures for electromigration stress tests and is intended to be packaged separately. Quadrants 1 through 3 have structures with straight test lines that have designed lengths of 400, 800, and 1200 μm, respectively. The structures in quadrant 4 have 1200-μm long test lines with right-angle turns. These different structures will allow a determination of any dependences of t_{50} on test line length and on right-angle turns.

The basic features of the electromigration test structures are illustrated in Fig. 2. This structure is a four-terminal device for making Kelvin resistance measurements. It is designed to detect open-circuit and short-circuit failures caused by electromigration. Initially, only unpassivated, single-level-metal structures will be tested for open-circuit failures. Subsequent experiments with passivated structures will be used to detect short-circuit failures between adjacent lines and between two metal levels.

NBS-42 test chips were fabricated on six three-inch wafers by sputter depositing Al 1%Si on oxidized silicon, wet etching the metallization, and annealing the metallization in forming gas for 20 minutes at 450°C. The mean sheet resistance and the mean electrical linewidth were determined to be 36.8 $m\Omega$/square and 3.10 μm, respectively. This was based on the results of measurements of cross bridge test structures at 10 locations on each of the six test wafers. The mean resistance of the structure with the 400-μm test line was determined to be 5.07 Ω from a similar set of measurements. The mean metallization thickness was determined to be 0.86 μm based on profilometer measurements at five locations on each of the wafers.

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The ratio of the standard deviation to the parameter mean (coefficient of variation) was determined from the above measurements to estimate the uniformity of the above parameters. The test structure resistance and the metallization sheet resistance, width, and thickness were determined to be uniform to within seven percent between wafers and within three percent on a wafer. The resistance, sheet resistance, and linewidth were determined to be uniform to within one percent in a quadrant grouping of the five test structures.

Each participating laboratory was sent test parts from one wafer to avoid the effect of possible wafer-to-wafer variations of t_{50}. Every laboratory was asked to stress two sets of 20 test structures to open-circuit failure: one set to be stressed at a current density of 1.0 and the other at 2.5 MA/cm^2. [n.b. M = million] These two stress levels were selected to determine if the repeatability of t_{50} measurements is affected by significant Joule heating, which occurs at the higher current density. Most of the laboratories volunteered to perform tests on packaged parts. Three volunteered to perform tests at the wafer level.

Each laboratory was instructed to use its own method to determine t_{50} for each of the two sets of test parts provided. Each laboratory was also asked to report its results with a detailed description of the method used and to provide a copy of the calculations used to obtain the results reported. To evaluate repeatability of t_{50} measurements, all t_{50} data from the participating laboratories are compared to those of the reference laboratory (NBS).

The following results will be reported:

- An estimate of the between-laboratory repeatability of t_{50} and sigma measurements, where each laboratory uses its own measurement method but where all use equivalent test structures.
- An estimate of the within-laboratory repeatability of t_{50} and sigma measurements using one test method and equivalent structures.
- An estimate of the interwafer variation of t_{50} measurements for wafers from the same metallization lot.
- The effect of Joule heating on the repeatability of t_{50} measurements.
- The effect of test-line length on t_{50} and sigma measurements.

Acknowledgments:

Portions of this work were supported by the Defense Advanced Research Projects Agency (ARPA Order NO. 3882). Packaging and other services were provided by the MOSIS system, University of Southern California/Information Sciences Institute.

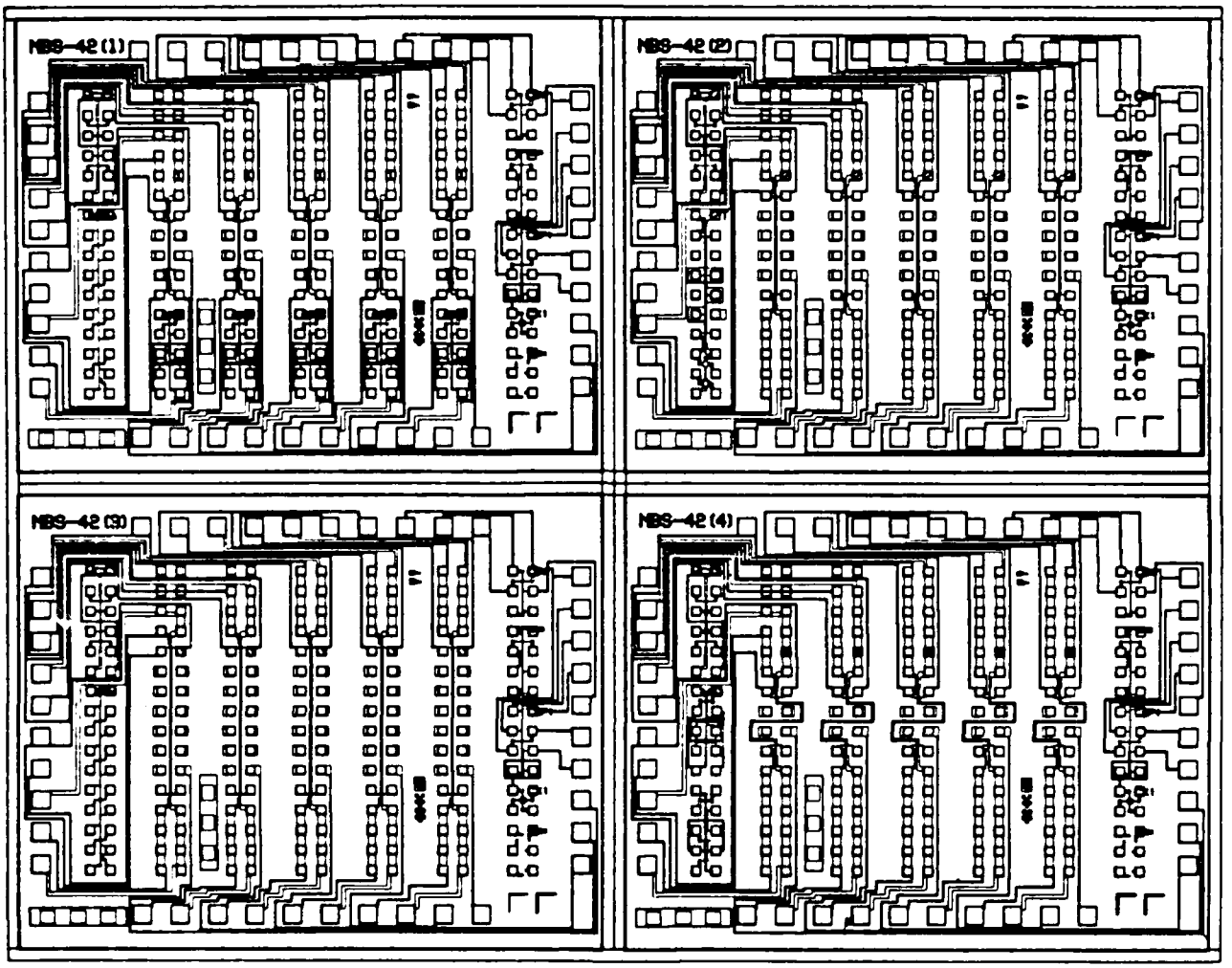

Fig 1. Two-level mask drawing of NBS-42 test chip (7.64 by 9.68 mm) where the lighter line is the metal and the other is the passivation level. Each quadrant has five centrally-located electromigration test structures.

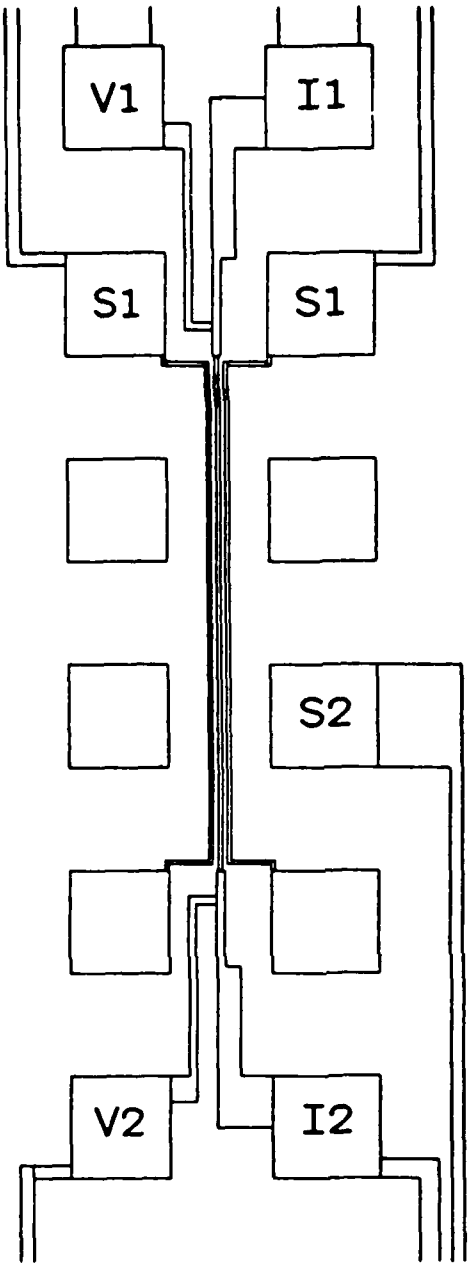

Fig. 2. Metal-level mask drawing of the electromigration test structure with a 400-μm long test line. Current through the test line is provided by pads I1 and I2. Voltage measurements and open-circuit failure detection of the test line are made with contacts V1 and V2. Short-circuit failure to the adjacent-running lines is detected with pad S1. Pad S2 can be used, with a second-level metal, to detect short-circuit failure between the test line and an overlying metal stripe (not shown).

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Interlaboratory Electromigration Experiment

PURPOSE

- ASSESS REPRODUCIBILITY OF ELECTROMIGRATION CHARACTERIZATIONS
- BROADEN TECHNICAL BASE FOR DEVELOPMENT OF GUIDELINES FOR:
  - design of test structures
  - measurement of t50
  - characterization of metallizations
  - report of characterization results

Interlaboratory Electromigration Experiment

PARTICIPATING LABORATORIES

1. Burroughs Corp., San Diego CA
   Paul Giotta

2. General Electric Co., Syracuse NY
   Donald La Combe

3. Hewlett-Packard Laboratories, Palo Alto CA
   Paul Merchant and Henry Chiang

4. IBM, Essex Junction NY
   Dennis Bouldin

5. IBM, Hopewell Junction NY
   James Lloyd

6. IBM Thomas J. Watson Research Center, Yorktown Heights NY
   Thomas Kwok

7. Intel Corporation, Aloha OR
   Jose Miaz and Babak Sabi

8. Motorola, Austin TX
   Ed Travis

9. Sandia Laboratories, Albuquerque NM
   James Arzigian

10. Signetics Corp., Sunnyvale CA
    Janet Towner

11. Syracuse University, Syracuse NY
    James Schwarz

12. Texas Instruments, Houstin TX
    Steve Lepkowski and P. B. Ghate

13. United Technologies Microelectronics Center
    Malcolm Garren

14. University of Florida, Gainsville FL
    Rolf Hummel

Interlaboratory Electromigration Experiment

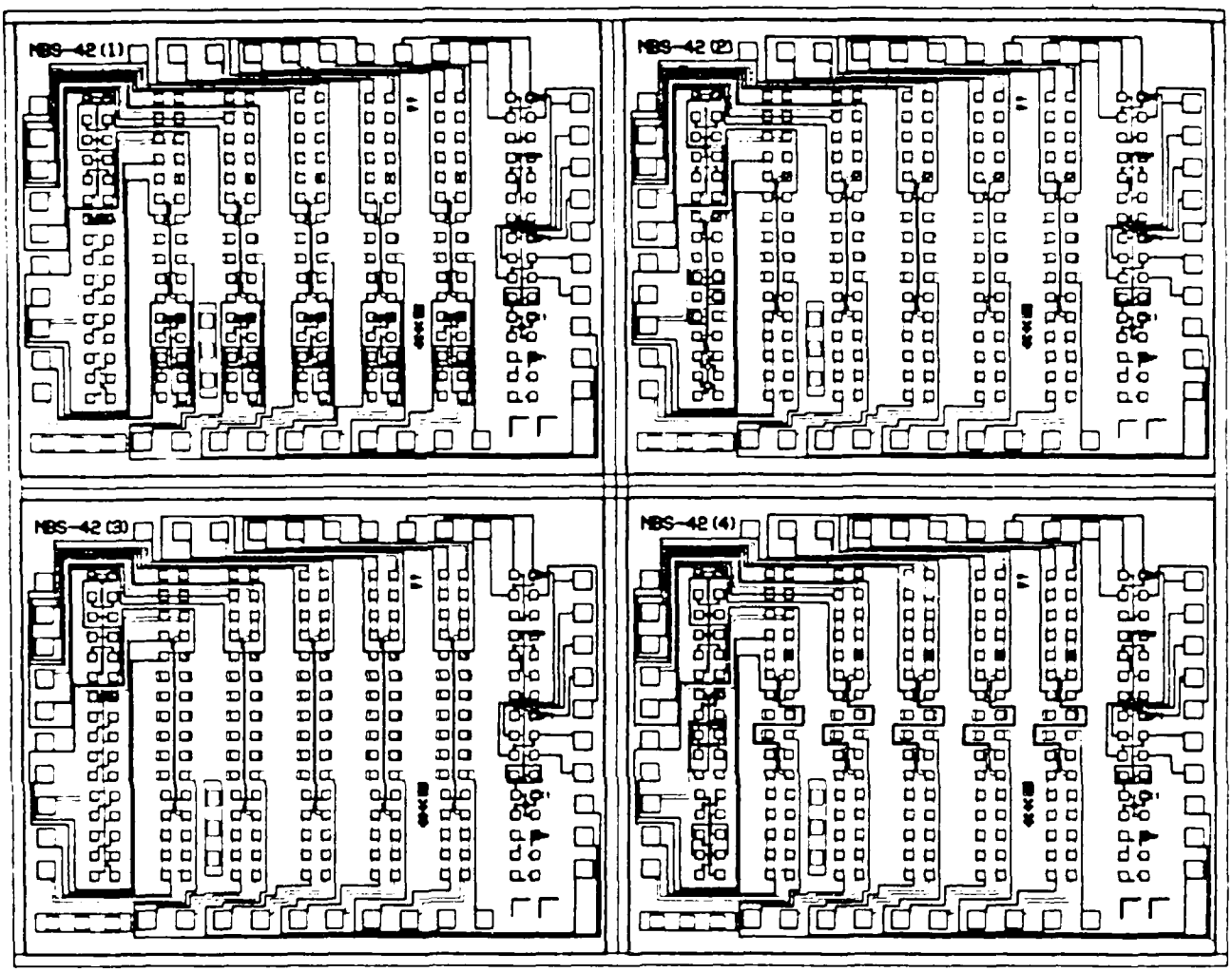
FIRST PHASE

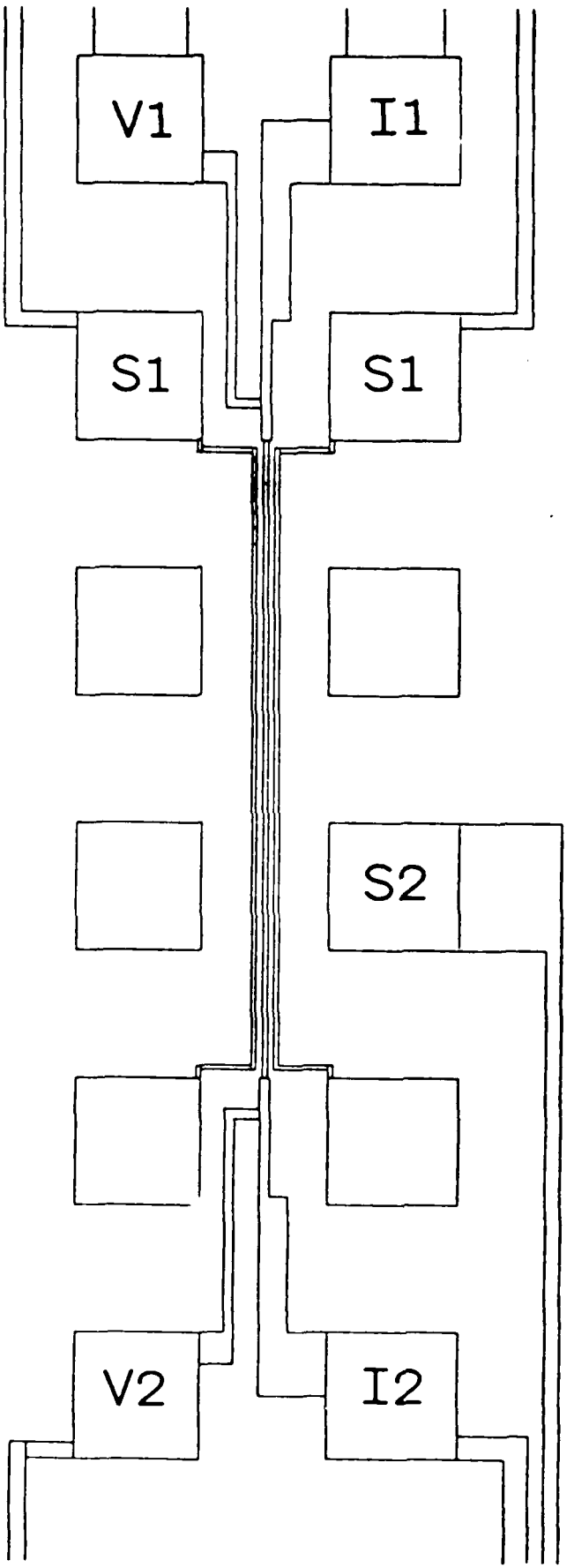
- UNPASSIVATED AL 1%Si METALLIZATION
- TEST PARTS FROM ONE METALLIZATION LOT
- LABS STRESS EQUIVALENT TEST PARTS:
  - 20 parts at J = 1.0 MA/cm*2 and T(oven) = 175 deg C
  - 20 parts at J = 2.5 MA/cm*2 and T(oven) = 150 deg C
- LABS USE OWN METHOD TO DETERMINE T50
- LABS NORMALIZE DATA:
  - T(metallization) = 175 DEG C
- NBS SERVES AS REFERENCE LABORATORY

Interlaboratory Electromigration Experiment

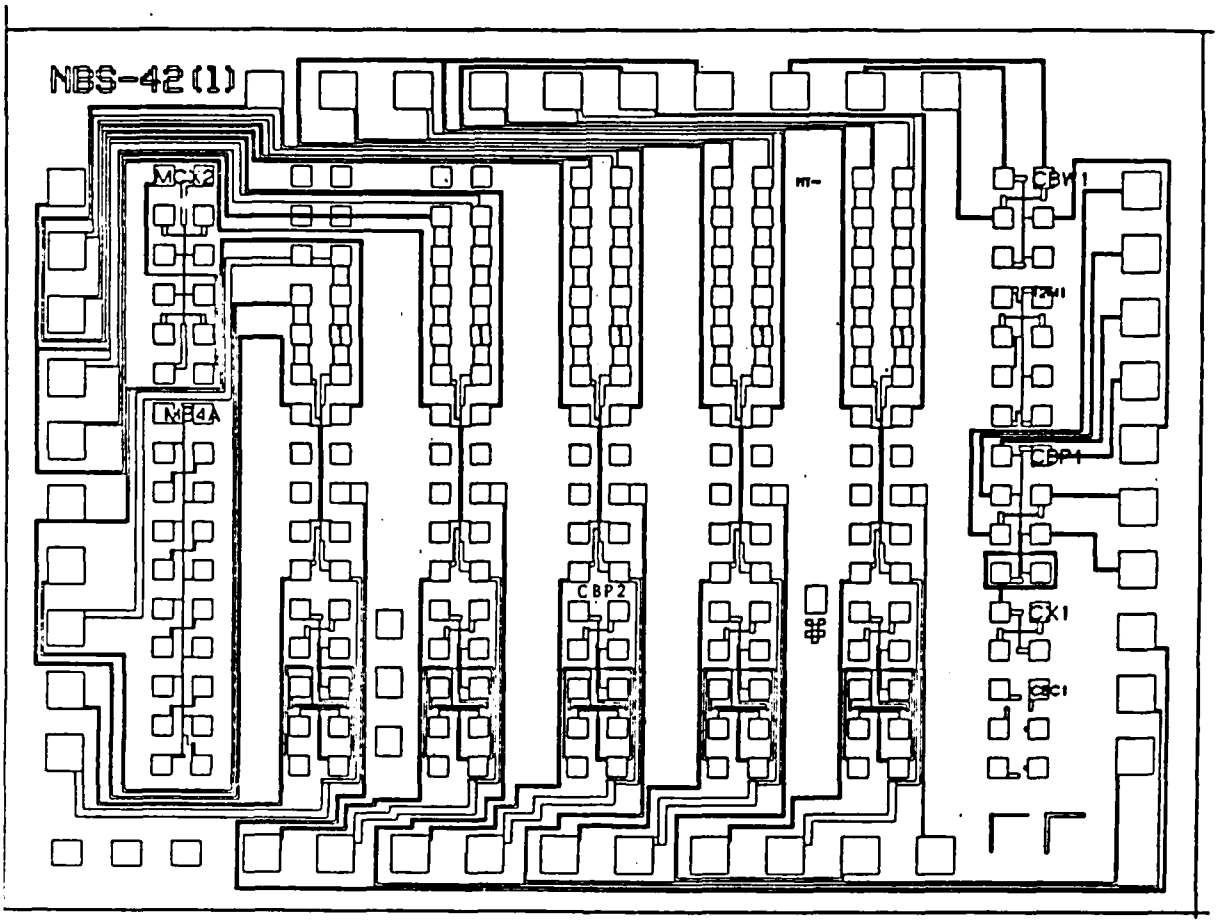
EXPECTED OUTCOMES

- BETWEEN-LABORATORY REPEATABILITY
  - Equivalent Test Parts (packaged parts, chips, sectors)
  - Same stress levels
  - Different Methods
- WITHIN-LABORATORY REPEATABILITY
  - Equivalent test parts
  - One method
- INTERWAFER VARIATION OF T50 AND SIGMA
- EFFECT OF JOULE HEATING ON REPEATABILITY
- EFFECT OF TEST-LINE LENGTH ON T50 AND SIGMA
- EFFECT OF CURRENT DENSITY ON ACTIVATION ENERGY
- COMPILATION OF TEST METHODS USED


MBS-42 (1)
MBS-42 (2)
MBS-42 (3)
MBS-42 (4)



BASIC ELECTROMIGRATION TEST STRUCTURE



QUADRANT 1 OF ELECTROMIGRATION TEST CHIP (NBS 42)

PARAMETER GRAND MEANS AND ESTIMATES OF PARAMETER UNIFORMITY FOR THE LOT OF SIX TEST WAFERS

PARAMETER	GRAND MEAN	PARAMETER UNIFORMITY WITHIN		
		LOT	WAFER	QUADRANT
RESISTANCE,R, of test structure	5.07 ohm	7.2%	3.3%	0.9%
SHEET RESISTANCE, Rs, of metallization	36.8 milliohm/□	1.2%	2.7%	0.5%
LINEWIDTH, w, of metallization	3.10 microns	6.9%	2.0%	0.6%
THICKNESS, tm, of metallization	0.86 microns	1.8%	2.7%	--
THICKNESS, tox, of oxide	1.56 microns	0.6%	0.9%	--

PARAMETER MEANS FOR WAFER LOT

LINEWIDTH

PARAMETER	MEAN VALUE (microns)
w	3.003
wp - w	0.092
wp	3.095
wp(h) - wp(v)	0.141
wp(h)	3.236

LINE SEPARATION

PARAMETER	MEAN VALUE (microns)
s(v)	4.047
s(v) - s(h)	0.389
s(h)	3.656

TEST STRUCTURE RESISTANCE

PARAMETER	MEAN VALUE (ohms)
R(400)	5.07
R(800)	9.81
R(1200)	15.05
R(1200^)	14.11

MEASUREMENT OF ACTIVATION ENERGY

AT TWO LEVELS OF CURRENT DENSITY

J (MA/cm*2)	T1(metall.) (deg C)	T2(metall.) (deg C)	Delta T (deg C)	Q (eV)
1.0 (1)	179	218	39	0.495
2.5 (2)	144	185	41	0.502

---

(1) 40 test structures used to determine t50 at T1 and at T2.
(2) 35 test structures used to determine t50 at T1 and at T2.

RESULT: Q(J=2.5 MA/cm*2) - Q(J=1.0 MA/cm*2) = 0.007 eV

CONCLUDE: Activation energy is not a function of current density.

ıboratory Electromigration Experiment

RESULTS .ROM THREE T50 DETERMINATIONS(1) FOR STRUCTURES WITH 400, 800, AND 1200 MICRON TEST LINES

	L=400 microns		L=800 microns		L=1200 microns	
	t50N(2) (h)	sigma	t50N (h)	sigma	t50N (h)	sigma
	7.31	0.26	5.50	0.31	5.26	0.26
	6.68	0.24	5.10	0.26	5.64	0.24
	6.53	0.29	6.36	0.25	5.63	0.27
$\overline{\text{Sigma}}$:		0.27		0.27		0.25
$\overline{\text{t50N}}$ (h):	6.84		5.65		5.51	
sd (h):	0.41		0.64		0.22	
sd/$\overline{\text{t50N}}$:	6.0%		11.3%		4.0%	

ESTIMATED WITHIN-LABORATORY REPEATABILITY: 0.46 h (7.7%)

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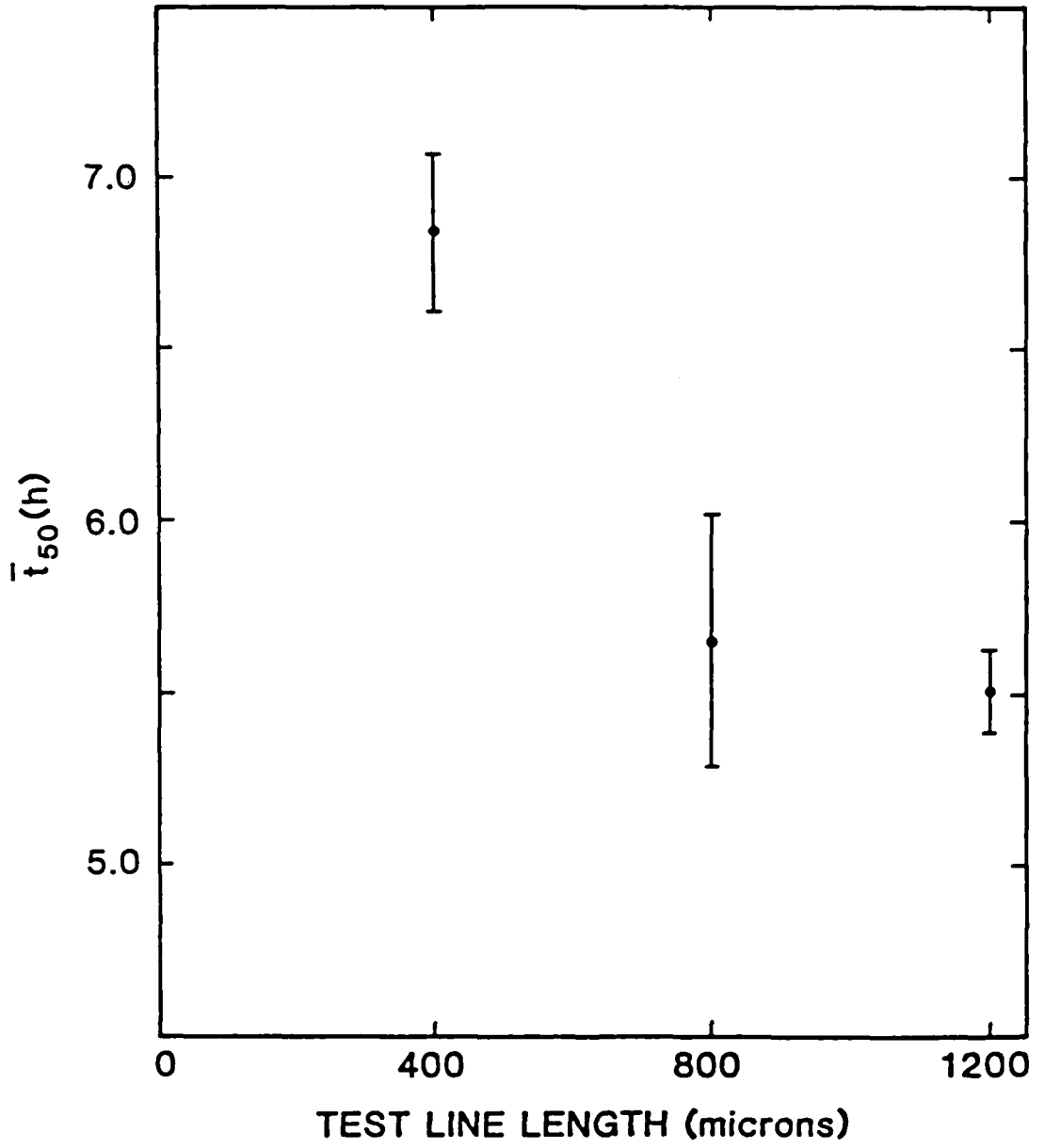
(1) 20 structures used per t50 determination, per test-line length. Stress conditions: J = 2.5 MA/cm*2 and T(oven) = 150 deg C.

(2) Normalized to a metallization temperature of 175 deg C and a test line area of 2.71 microns squared.


7.0
6.0
5.0
$\bar{t}_{50}$(h)
0
400
800
1200
TEST LINE LENGTH (microns)

Interlaboratory Electromigration Experiment

INTERWAFER VARIATION OF T50 AND SIGMA

WAFER	J=1.0 MA/CM*2		J=2.5 MA/CM*2	
	T50n(1) (h)	SIGMA	T50n(1) (h)	SIGMA
1	33.74	0.31	6.41	0.27
2	33.90	0.36	5.97	0.25
3	34.24	0.30	5.52	0.25
4	33.35	0.35	6.50	0.23
5	30.47	0.36	5.39	0.32
7	27.78	0.27	5.74	0.24
8	31.37	0.37	5.51	0.35
MEAN	32.12	0.33	5.86	0.27
SD	2.38	0.04	0.45	0.05
SD/MEAN	7.4%		7.7%	

---

(1) T50 normalized to:

1. metallization temperature of 175 deg. Celsius and
2. test-line area of 2.58 microns squared.

Interlaboratory Elecetromigration Experiment

BETWEEN-LABORATORY REPRODUCIBILITY

J = 2.5 MA/CM*2

LAB ID	LABORATORY		REFERENCE		T50n (LAB) / T50n (REF)
	T50n (1) (h)	SIGMA	T50n (1) (h)	SIGMA	
C	3.55	0.29	5.64	0.24	0.63
D	3.00	0.35	5.64	0.24	0.53
A	6.53	0.3	6.76	0.27	0.97
A(2)	5.77	0.32	6.76	0.27	0.85
O	4.44	0.34	6.11	0.23	0.73
W	0.85	0.45	6.11	0.23	0.14
J	4.32	0.41	5.64	0.24	0.77
P	7.0	0.31	5.52	0.25	1.27
E	4.95	0.30	5.52	0.25	0.83

J = 1.0 MA/CM*2

LAB ID	LABORATORY		REFERENCE		T50n (LAB) / T50n (REF)
	T50n (1) (h)	SIGMA	T50n (1) (h)	SIGMA	
A	40.28	0.4	35.70	0.31	1.13
A(2)	38.52	0.4	35.70	0.31	1.08
O	32.22	0.32	30.39	0.35	1.06
W	20.5	0.26	30.39	0.35	0.68
J	25.6	0.42	27.88	0.27	0.92
P	29.0	0.35	34.24	0.30	0.85
E	32.92	0.36	34.24	0.30	0.96

(1) T50 normalized to a metallization temperature of 175 deg. Celsius.
(2) Alternative means of determining metallization temperature and independent readings of t50's and sigmas from charts.

Interlaboratory Electromigration Experiment

SUMMARY

- o PARAMETER UNIFORMITY:
  - Metallization Sheet Resistance and Thickness

    Over a Wafer: 3 %
    Within Wafer Lot: 3 %

  - Metallization Linewidth

    Over a Wafer: 3 %
    Within Wafer Lot: 8%

- o ACTIVATION ENERGY: 0.50 eV (not dependent on J)

- o WITHIN-LABORATORY REPEATABILITY of T50: 8 %

- o T50 is a FUNCTION of TEST LINE LENGTH below about 800 microns

- o INTERWAFER VARIABILITY OF T50: 8 %

- o BETWEEN-LABORATORY REPEATABILITY
  - For J = 1.0 MA/CM*2 Stress:

    Generally Within One-Laboratory Repeatability Limits

  - For J = 2.5 MA/CM*2 Stress:

    Variable, But Generally No Worse Than a 2:1 Difference

  - Number of Sources for Variability Noted

END

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